US 301 Bridge

Petrographic Examination of Concrete Cores

Orangeburg County, South Carolina

FINAL REPORT

March 11, 2022

WJE No. 2022.0320.0

PREPARED FOR:

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Karla Salahshour
Petrographer, Project Manager

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INTRODUCTION

At the request of Mr. Michael Ulmer of ESP Associates, Inc. (ESP), Wiss, Janney, Elstner Associates, Inc. (WJE) completed petrographic examinations of concrete cores extracted from bridge piers of US 301 over Four Hole Swamp in Orangeburg County, South Carolina. ESP is performing an assessment of the bridge as part of a South Carolina Department of Transportation bridge replacement project. The concrete bridge was originally built in 1926 and was expanded in 1950. The bridge is located over a blackwater river[1] containing fresh water but with elevated tannin levels resulting in a slight acidity. The concrete bridge piers exhibit, according to ESP, "significant corrosion of steel H-piles and loss of cement paste/concrete degradation…within the waterline fluctuation zone" (Figure 1). ESP requested WJE perform an examination of the concrete bridge piers to determine the cause of the concrete distress.


Figure 1. Bridge pier with corroded steel and deteriorated concrete near the waterline (arrow). Image provided by ESP.

EXECUTIVE SUMMARY

The following summarizes pertinent information from the petrographic examination:

- The concrete in the examined core samples contains crushed granitic coarse aggregate and siliceous fine aggregate in a non-air-entrained, portland cement paste.
- The distress is primarily confined to the exterior surface and near-surface regions of the cores extracted from the waterline fluctuation zone due to acid attack of the exposed cement paste.
- No distress was observed with the core extracted from above the waterline.

SAMPLES

Four concrete cores labeled B-7-1R, B-7-2L, B-8-1, and B-8-2 were received in the WJE Cleveland, Ohio laboratory for the studies. The cores were extracted horizontally from bents 7 and 8, as reported by ESP. Core B-8-1 was extracted above the waterline. The remaining three cores were extracted within the waterline fluctuation zone. The exterior surfaces of the cores represent the exposed concrete on the bridge piers (Figure 2). The cores were broken within the pier elements, and the interiors of the cores are

[1] According to Wikipedia, a "blackwater river is a type of river with a slow-moving channel flowing through forested swamps or wetlands. As vegetation decays, tannins leach into the water, making a transparent, acidic water that is darkly stained, resembling black tea."

fractured surfaces. Cores B-7-2L and B-8-2 intersected reinforcement with no observed corrosion-related distress. A summary of the extraction locations and as-received conditions is provided in Table 1. The as-received appearance of the cores is provided in Figure A1 through Figure A4 located in Appendix A.

Figure 2. As-received appearance of exterior surfaces of the four core samples. Cores B-7-1R, B-7-2L, and B-8-2 were extracted in the waterline fluctuation zone, whereas Core B-8-1 was extracted at a higher elevation on the bridge pier.

PETROGRAPHIC EXAMINATION

The cores were examined using methods outlined in ASTM C856, *Standard Practice for Petrographic Examination of Hardened Concrete*. Microscopic examination and various tests conducted during the petrographic examination are designed to elicit specific information about the composition and condition of the concrete. See Appendix B for additional information regarding the methodology of this examination. Pertinent observations from the examination are summarized in Table 1.

Unit weight was measured for representative portions of each core according to Section 9, *Unit Weight and Loss of Free Water*, of ASTM C1084, *Standard Test Method for Portland-Cement Content of Hardened Hydraulic-Cement Concrete*. The results are provided in Table 1.

Volumes of air, paste, and aggregates were measured for the lapped surfaces of Core B-7-2L using Procedure B, *Modified Point-Count Method*, of ASTM C457, *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*. See Appendix B for additional information regarding specific details of this test. The results are provided in Table 1.

Representative figures are included in the report. Supplemental figures are provided in Appendix A and are referenced throughout the report.

Exterior Surface

Cores B-7-1R, B-7-2L, and B-8-2

The exterior surface of Cores B-7-1R, B-7-2L, and B-8-2, all extracted within the waterline fluctuation zone, is irregular in profile due to loss of surface paste resulting in the partial exposure of coarse aggregates (Figure 2, Figure 3, and Figure 4). The relief of the irregular surface profile, indicating the minimum depth of paste erosion from the original formed surface at the time of coring, is 1/4 inch in Core B-7-1R, 1/8 inch in Core B-7-2L, and 1/4 inch in Core B-8-2.

Figure 3. Brown discoloration on the exposed surface of coarse aggregates and paste.

Figure 4. Aggregates (arrows) protruding from the exterior surface.

The exterior surfaces contain brown discoloration on the exposed coarse aggregates and paste (Figure 2 and Figure 3). Beneath the brown-colored material on the exterior paste, the paste is tan to yellow in color, granular in texture, friable, and extremely absorptive.

A white film or haze was observed on portions of the brown discolored surface that may represent efflorescence (salts precipitated on the surface) (Figure A5). Minor amounts of white secondary deposits of ettringite, carbonate, and isotropic material were observed lining some voids on the surface of Core B-7-1R; trace to no secondary deposits were observed for Cores B-7-2R and B-8-2. The surface of Core B-8-2 contains green plant growth.

In thin section, a portion of the surface contains a thin layer of isotropic paste (measured to a maximum depth of approximately 0.5 mm) that suggests leaching of calcium-containing components from the surface (Figure 5 and Figure 6). Siliceous fine aggregates are embedded within the isotropic paste. The paste immediately below this surface region is dense and carbonated.

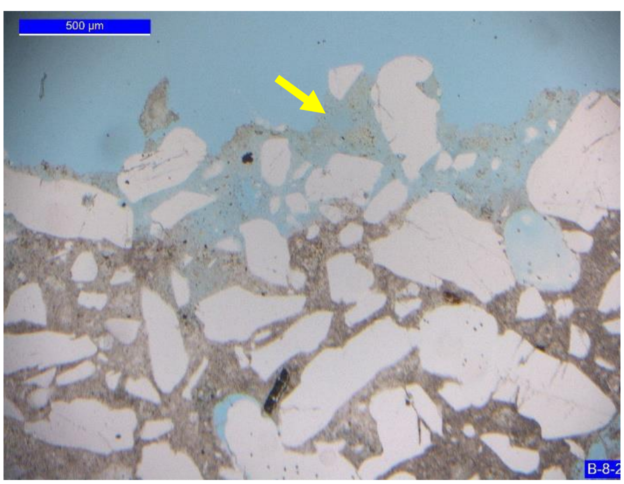

Figure 5. Porous paste (arrow) outboard of carbonated paste along the exterior surface; plane-polarized light.

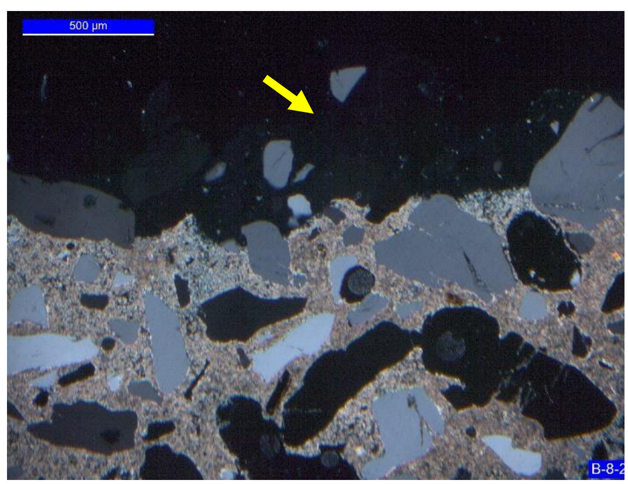

Figure 6. Isotropic paste (arrow) outboard of carbonated paste along the exterior surface; cross-polarized light.

Trace microfractures within the paste and fine aggregates was observed in thin section for Cores B-7-2L and B-8-2 (Figure A6).

Core B-8-1

The exterior surface of Core B-8-1, extracted above the waterline fluctuation zone, was not discolored brown and did not contain isotropic paste. Rather, a gray colored, air-entrained mortar was observed on portions of the exterior surface to a depth of approximately 1/16 inch (Figure 7). Microcracks within the surface mortar were present (Figure A7). The gray paste along the exterior surface has a slight green hue due to plant growth. The surface has a microtexture of linear striations possibly due to a trowel application. Fine aggregates (and no coarse aggregates) are partially exposed on the surface. The surface mortar paste is friable, extremely soft, and extremely absorptive. Entrained air voids are visible in the exterior paste, and no secondary deposits were observed within the voids. A white haze was not present on the surface of Core B-8-1 as was observed in the other three cores. In thin section, remnants of this surface mortar contained some portland cement particles that were visually dissimilar to that in the body of the cores (Figure A8) but still coarsely graded.

No distress was observed in the concrete beneath the surface mortar (Figure 8).

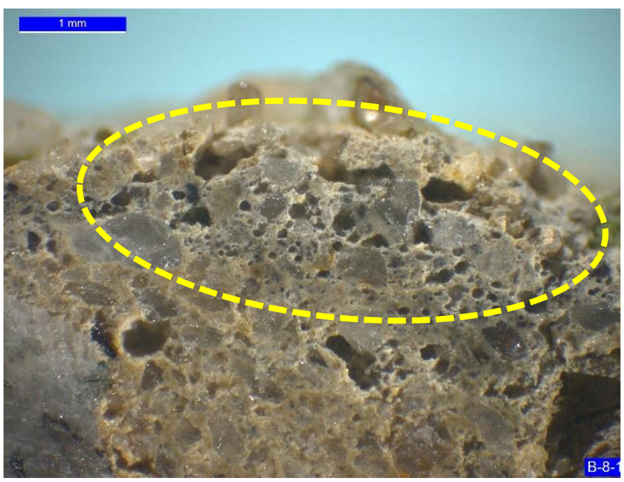

Figure 7. Gray, air-entrained mortar on the surface of Core B-8-1.

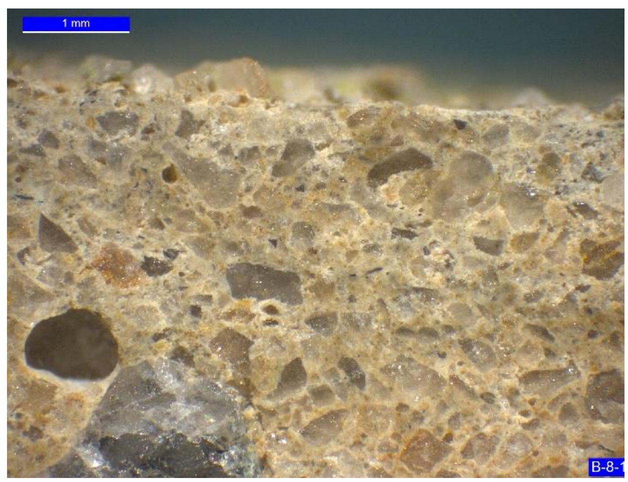

Figure 8. No distress in the concrete beneath the surface mortar on the surface of Core B-8-1.

Concrete Mixture Description

The concrete in the examined core samples represents compositionally similar material containing crushed igneous rock fragments and siliceous fine aggregate in a non-air-entrained, portland cement paste (Figure A9). Descriptions below pertain to the concrete body in the four cores, unless otherwise noted.

Aggregates

The coarse aggregate is a crushed rock with a maximum size of 3/4 to 1 inch. The particles are angular to sub-angular in shape, hard, and dense. Several particles are elongate in shape and oriented parallel to each other (the orientation of cores in the field was not provided). The coarse aggregate is light to dark gray in color and composed of granitic rock fragments. A trace amount of wood fragments was observed in the cores. The coarse aggregate contains fewer intermediate sized particles (more of a gap graded mix) in Core B-8-2 compared to the other three cores. The aggregates are generally uniformly distributed except in Cores B-7-1R and B-8-2 where the exterior of the core (outboard of the embedded reinforcing bar in Core B-8-2) is coarse aggregate deficient. The amount of coarse aggregate varies slightly with the largest coarse aggregate volume observed visually on lapped surfaces in Core B-8-2. No evidence of an internal reactions, such as alkali-silica reaction, involving the coarse aggregate was observed.

The fine aggregate consists of siliceous sand of primarily quartz and feldspar and minor amounts of mica. The fine aggregate contains few coarser-sized particles. No evidence of an internal reaction involving the fine aggregate was observed.

Paste

The paste ranges from light to dark gray in color. Mottling of the paste was observed for all four cores. For Core B-8-2, the exterior 3/8 inch is darker gray in color, although the body of the core contains lighter gray paste compared to the other cores. The. The paste cannot be scratched using a copper probe (hard). Calcium hydroxide in thin section is present as small, discrete crystals. Residual portland cement particles are coarse in size, abundant, and often exceed 150 microns in size (Figure A10). The residual particles represent belite nests. No supplementary cementitious materials, such as fly ash or slag cement, were observed.

Given the textural features of the paste, the estimated water-to-cement ratio (w/c) is low, ranging from 0.42 to 0.47, for Cores B-7-1R, B-7-2L, and B-8-1. The bulk w/c for Core B-8-2 was judged to be slightly higher, estimated between 0.45 to 0.50. However, local variations outside this range were observed, primarily adjacent water gain voids below coarse aggregates resulting in a locally elevated w/c. This estimated w/c is especially low given the eras of original construction and bridge widening.

The depth of paste carbonation was measured after the application of phenolphthalein indicator solution on the laboratory-induced fresh fracture surfaces (refer to Table 1). The maximum depth from the exterior surface was measured to be 1-1/4 inch for Core B-8-1, which was extracted above the waterline, and consistent with tan to pink discoloration near the surface in this core (Figure A9). For the three cores extracted within the waterline fluctuation zone, the maximum depth of paste carbonation was 1/8 inch.

Voids

The paste is not air-entrained, and small, spherical voids characteristic of the use of an air-entraining admixture were not frequently observed. Voids are irregularly shaped voids and commonly located adjacent to coarse aggregates representing bleed water channels and water gain voids (Figure A11). In thin section, large concentrations of calcium hydroxide crystals were present in these voids for Core B-8-1. Secondary deposits were not frequently observed in the examined cores.

Large irregularly shaped voids are present within the body of Core B-8-2. Voids were also commonly observed near the reinforcing plane and near the exterior surface. These are judged to be a result of incomplete initial compaction.

The volume of voids was measured to be 5.6 percent for Core B-7-2L and judged to be similar in Cores B-7-1R and B-8-1. The volume of voids was estimated to be greater in Core B-8-2.

Distress

Cores B-7-1R, B-7-2L, and B-8-2

The distress in Cores B-7-1R, B-7-2L, and B-8-2 is confined to the exterior surface and near-surface regions (refer to Table 1). Paste erosion resulting in the exposure of coarse aggregates has resulted in an irregular surface profile with maximum depth of distress of 1/4 inch. Beyond this depth of surface irregularity, voids (incomplete consolidation and/or water voids) intersected by the surface were observed within the near-surface region of Core B-8-2 resulting in a total depth of distress of 1/2 inch for this core. No near-surface distress was observed in Core B-7-2L beyond the surface irregularity of 1/8 inch (which also includes the depth of isotropic paste).

For Core B-7-1R, a separation is present within Core B-7-1R that is angled from the exterior surface up to a depths of 3 inches (Figure 9 and Figure A9). The separation may represent a crack or a settlement/movement feature within the concrete. The presence of mortar stringers spanning the width suggests that the feature formed while the concrete was still plastic (unset). The surfaces along the separation are lined with secondary deposits, indicating moisture has been able to migrate through it over time (Figure 10). The core remained intact during core extraction, shipment, and sample preparation despite this feature.

Figure 9. A separation (arrow) near the exterior surface of Core B-7-1R.

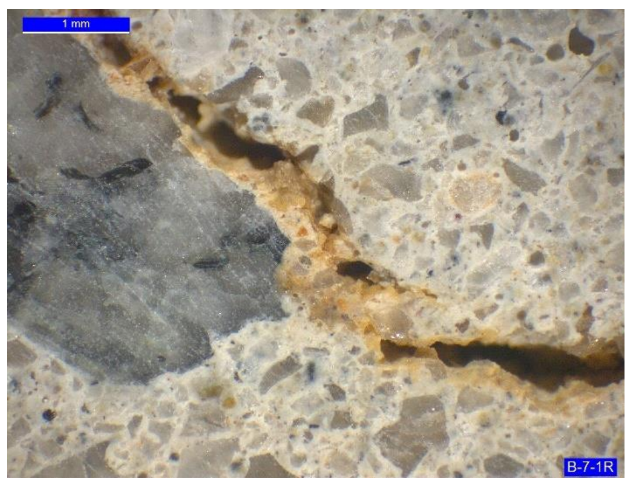

Figure 10. Mortar stringers and secondary deposits lining the separation in Core B-7-1R.

Core B-8-1

No distress was observed on the surface or within the body of Core B-8-1.

DISCUSSION AND CONCLUSION

Concrete Observations

The cores represent compositionally similar concrete containing crushed granitic coarse aggregate and siliceous fine sand embedded within a non-air-entrained, portland cement paste. The concrete ingredients appear to be similar in all of the examined cores suggesting that the concrete is from the same vintage (e.g. original concrete). However, the difference in reinforcement type is unusual for concrete of a similar vintage. The reinforcement intersected by Core B-7-2L is square in cross-section (not unusual for concrete of this vintage), and the reinforcement is ribbed with a circular cross-section (consistent with more modern reinforcement) in Core B-8-2. It is possible that similar concrete ingredients were used for the 1950s construction as the original 1930s construction but with deformed circular reinforcing bars, and the concrete in Core B-8-2 is from the widening of the bridge.

The material on the surface of Core B-8-1 represents an air-entrained, cement mortar. The benefits of air entrainment and the use of air-entraining admixtures started in the 1930s. Given this timeframe, and the coarse gradation of the residual portland cement particles, it is possible that this material represents a repair that was installed recently after original construction or during the bridge widening. No evidence of previous repairs was observed in the other three examined cores.

Distress

The distress is confined to the surface and near-surface region of the three cores from the waterline fluctuation zone (except for the presence of the separation to a depth of 3 inches in Core B-7-1R). Exposure to the blackwater river resulted in the discoloration and paste erosion on the surface. The slightly acidic river water results in acid attack of the exposed paste. As the paste is attacked by the water, aggregates will stand proud from the resulting surface and may eventually become dislodged. Acid attack of concrete can also result in the formation of a gelatinous silica layer (i.e. isotropic paste) on the surface outboard of carbonated paste[2] due to leaching from the surface, as was observed in the three cores. Plant growth that was observed on the surface of the cores can also result in attack of the cement paste due to the release of organic acids.

Very minor carbonation of the paste was observed in the cores from the waterline fluctuation zone. As a result, the alkaline concrete still has its natural passivation for the embedded steel reinforcement at this location. No corrosion-related distress was observed in the cores from within the waterline fluctuation zone that intersected reinforcement. For the core extracted above the waterline, Core B-8-1, the paste was carbonated up to 1-1/4 inches. This core did not intersect reinforcement to allow for commentary on the current extent of corrosion, if any.

The concrete is not air-entrained, and it would not be expected to be freeze-thaw durable if critically saturated and exposed to freezing and thawing cycles (although the site is in a low freeze-thaw cycle area of the country). However, no freeze-thaw-related distress was observed in the examined samples.

Future distress should be expected for the exposed concrete surfaces at the waterline fluctuation zone. The rate of distress is primarily related to the flow rate of the water, in addition to the acidity of the water[2].

No distress was observed in the core sample extracted from above the waterline.

[2] Poole, A. B., et al. *Concrete Petrography: A Handbook of Investigative Techniques*. 2nd ed., CRC Press, 2016.

Table 1. Description of Core Samples

<table>
<tr><th colspan="2">Description</th><th>B-7-1R</th><th>B-7-2L</th><th>B-8-1</th><th>B-8-2</th></tr>
<tr><td rowspan="3">Extraction Location</td><td>Pier</td><td colspan="2">5</td><td colspan="2">4</td></tr>
<tr><td>Bent</td><td colspan="2">7</td><td colspan="2">8</td></tr>
<tr><td>Elevation</td><td colspan="2">Near water line</td><td>Above water line</td><td>Near water line</td></tr>
<tr><td colspan="2">Core Orientation</td><td colspan="4">Horizontal</td></tr>
<tr><td rowspan="2">Core Dimensions</td><td>Diameter</td><td colspan="4">3.75″</td></tr>
<tr><td>Length</td><td>7″ to 8″</td><td>4″ to 5″</td><td>5-3/4″</td><td>5-1/2″ to 6-1/4″</td></tr>
<tr><td colspan="2">Reinforcement</td><td>None</td><td>1″ square rebar with 2-5/8″ clear cover</td><td>None</td><td>1/2″ diameter (#4) ribbed rebar with 1-1/2″ clear cover</td></tr>
<tr><td colspan="2">Unit Weight (pcf)</td><td>150</td><td>148</td><td>149</td><td>148</td></tr>
<tr><td colspan="2">Carbonation Depth from Exterior</td><td>1/16″ to 1/8″</td><td>1/16″</td><td>1/2″ to 1-1/4″</td><td>1/16″</td></tr>
<tr><td colspan="2">Exterior Surface Features</td><td>Angled exterior surface; brown discoloration; irregular surface profile with exposed coarse aggregates; paste erosion up to 1/4″; discolored and friable paste; minor secondary deposits; visible microcrack</td><td>Angled exterior surface; brown discoloration; irregular surface profile with exposed coarse aggregates; paste erosion up to 1/8″; discolored and friable paste; trace secondary deposits</td><td>Gray, air-entrained mortar on portions of exterior surface; microtexture on surface with exposed fine aggregate with relief of approximately 1/16″; discolored and friable paste; truncated voids; plant growth</td><td>Angled exterior surface; brown discoloration; irregular surface profile with exposed coarse aggregates; paste erosion up to 1/4″; discolored and friable paste; trace to no secondary deposits; plant growth</td></tr>
<tr><td colspan="2">Near-Surface Features</td><td>Isotropic paste along exterior to depth of 0.2 mm</td><td>Isotropic paste along exterior to depth of 0.2 mm; trace near-surface microfractures within paste and fine aggregates</td><td>Gray, air-entrained mortar 1/16″ thick on portions of the surface</td><td>Isotropic paste along exterior to depth of 0.5 mm; trace near-surface microfractures within paste and fine aggregates; darker gray paste and voids</td></tr>
<tr><td rowspan="4">Concrete Features</td><td>Coarse Aggregate</td><td>Crushed granitic aggregate; maximum size 1″; hard, dense; elongated particles; non-uniform distribution; no evidence of internal reaction</td><td colspan="2">Crushed granitic aggregate; maximum size 1″; hard, dense; elongated particles; uniform distribution; no evidence of internal reaction</td><td>Crushed granitic aggregate; maximum size 3/4-1″; hard, dense; elongated particles; gap graded; non-uniform distribution; estimated larger volume compared to other cores; no evidence of internal reaction</td></tr>
<tr><td>Fine Aggregate</td><td colspan="4">Siliceous sand; fine gradation; no evidence of internal reaction</td></tr>
<tr><td>Paste</td><td colspan="3">Light to dark gray mottling; hard</td><td>Light gray; hard</td></tr>
<tr><td>Estimated w/c</td><td colspan="3">Low; estimated 0.42-0.47</td><td>Moderate; estimated 0.45-0.50</td></tr>
</table>

Description	B-7-1R	B-7-2L	B-8-1	B-8-2
Air Void System	Not air-entrained; irregularly shaped voids commonly adjacent coarse aggregates			Not air-entrained; a greater volume of voids than other three cores; irregularly shaped voids commonly adjacent coarse aggregates
Description of Distress in Body of Core	Planar concentration of voids at surface to 3″ lined with secondary deposits but core remained intact during examination	None	None	Voids within body of core but not associated with distress
Overall Depth of Distress	Paste erosion and separation within the core to a depth of 3″	Paste erosion up to 1/8″	None	Paste erosion and voids up to 1/2″

Table 2. Modified Point-Count Results

Volume (%)	Core B-7-2L
Air	5.6
Paste	24.6
Fine Aggregate	20.0
Coarse Aggregate	49.7
Total Aggregate	69.7
Paste/Air	4.4

APPENDIX A. SUPPLEMENTAL FIGURES

Figure A1. As-received appearance of exterior (upper left), interior (upper right), and side (lower) of Core B-7-1R. Separations within the exterior of the core are identified with arrows.

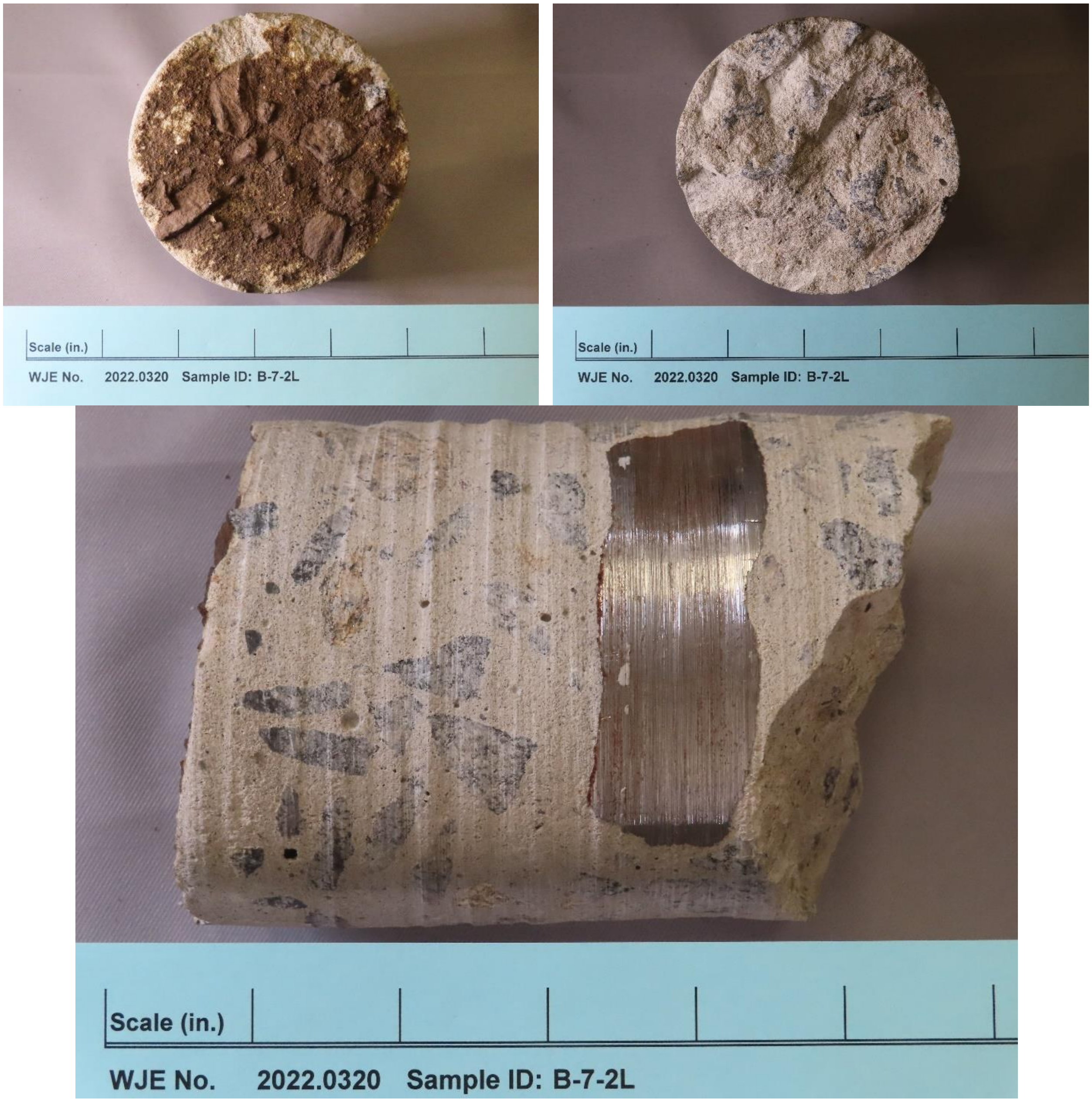

Figure A2. As-received appearance of exterior (upper left), interior (upper right), and side (lower) of Core B-7-2L. The intersected reinforcement is square in profile with 1 inch dimension.

Figure A3. As-received appearance of exterior (upper left), interior (upper right), and side (lower) of Core B-8-1.

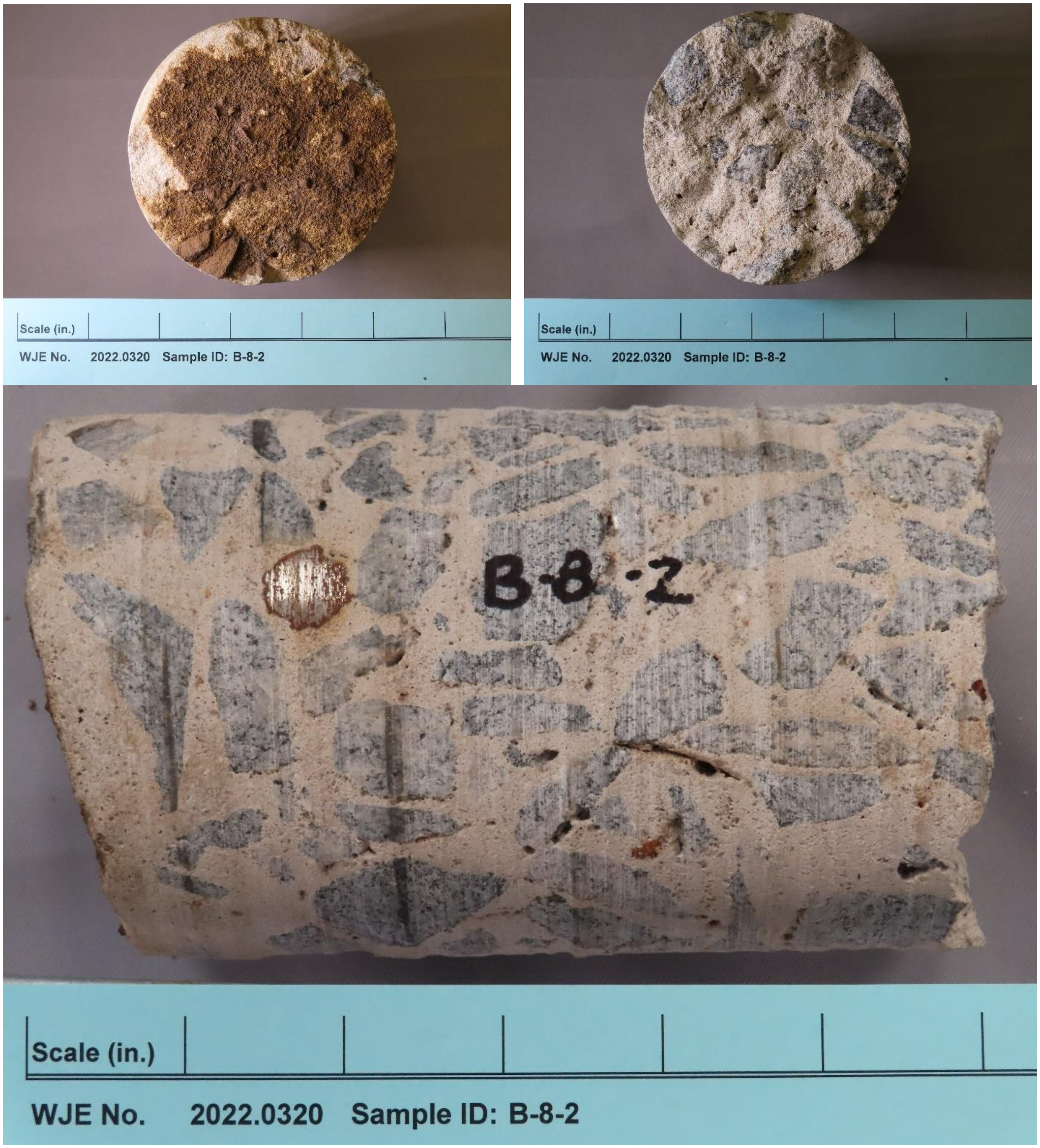

Figure A4. As-received appearance of exterior (upper left), interior (upper right), and side (lower) of Core B-8-2. The intersected reinforcement is round in profile with ribs and 1/2″ diameter.

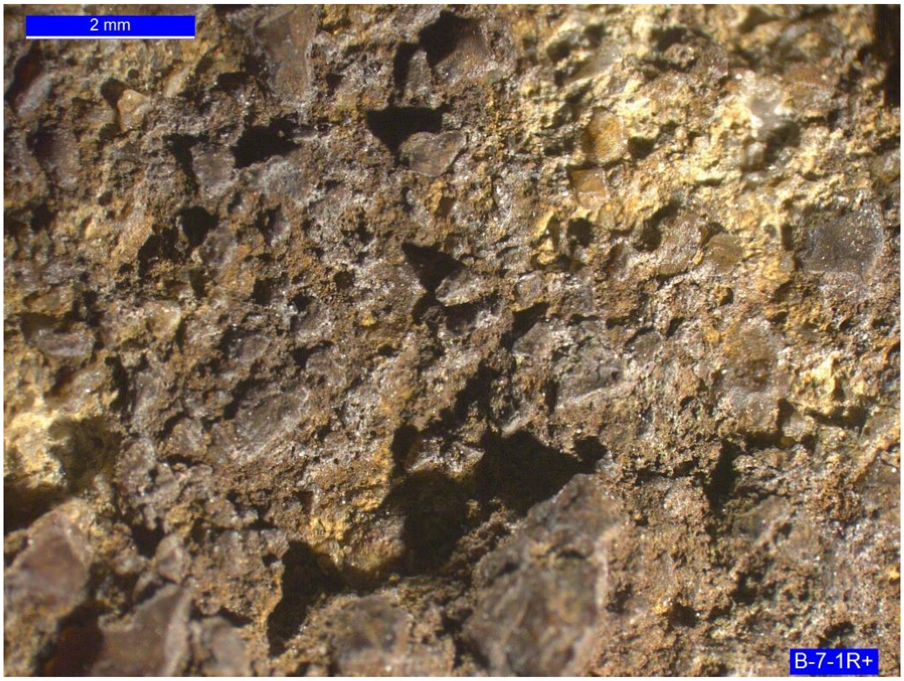

Figure A5. A white film outboard of the brown discolored surface, pictured for Core B-7-1R.

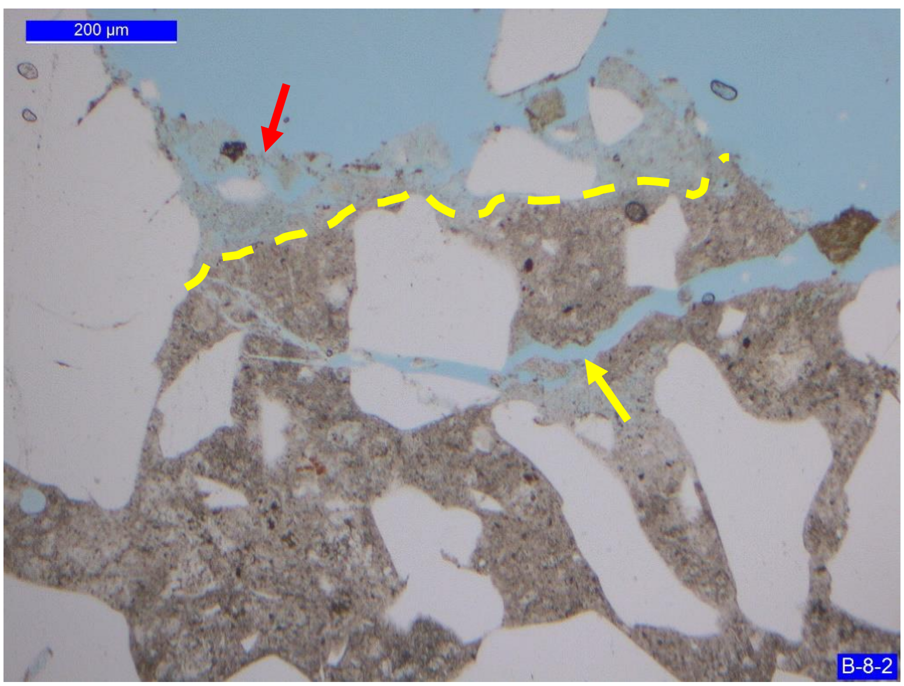

Figure A6. A fracture (yellow arrow) near the surface and isotropic paste (red arrow) along the exterior surface of Core B-8-2. The interface between the isotropic paste and the underlying carbonated concrete is marked with a dashed line.

Figure A7. Green plant growth and microcracks on the surface of Core B-8-1.

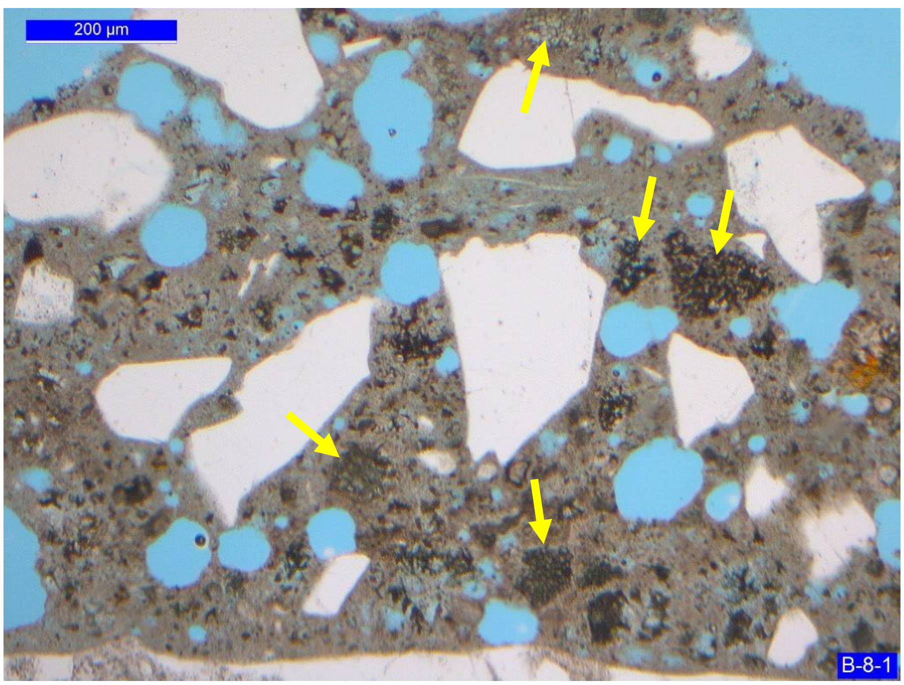

Figure A8. Residual cement particles (arrows) within the surface mortar in Core B-8-1.

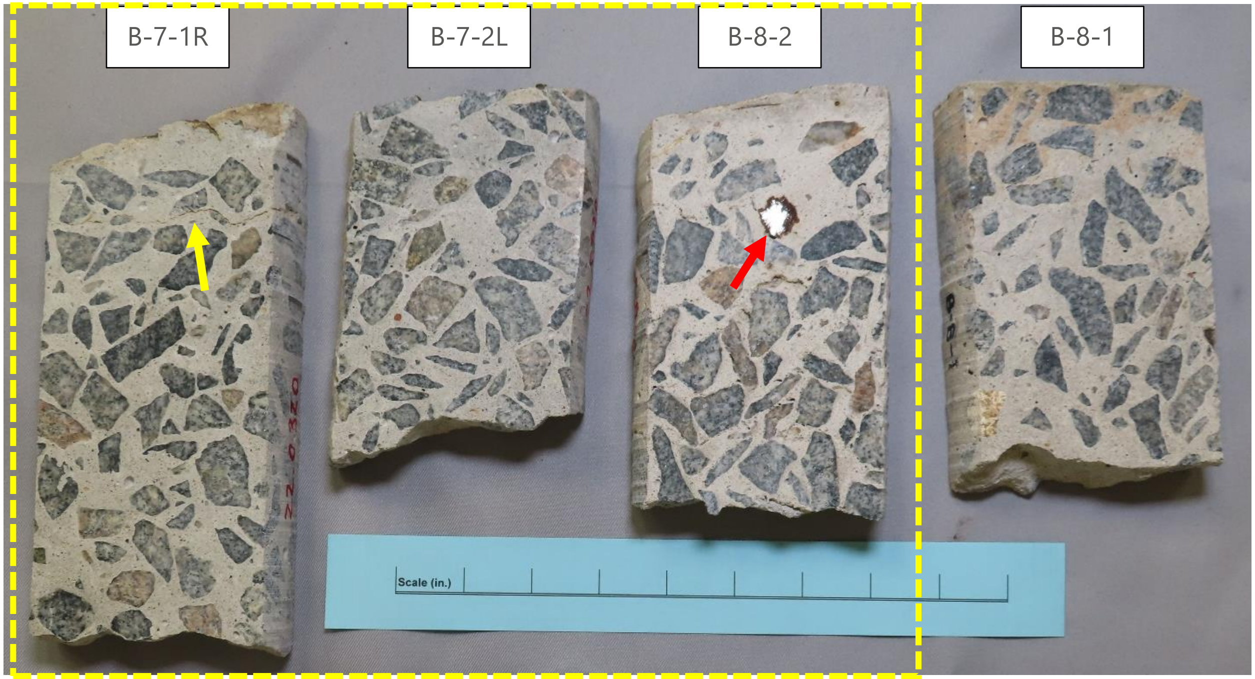

Figure A9. Lapped surfaces of the four examined core samples with compositionally similar concrete constituents. Variability in the volume and distribution of aggregates is apparent. The cores in the boxed region were extracted from within the waterline fluctuation zone, and Core B-8-1 was extracted at a higher elevation. A separation is identified with a yellow arrow in Core B-7-1R. A reinforcing bar intersected by Core B-8-2 is identified with a yellow arrow. The pink paste discoloration along the exterior surface (to top of the image) of Core B-8-1 is due to carbonation.

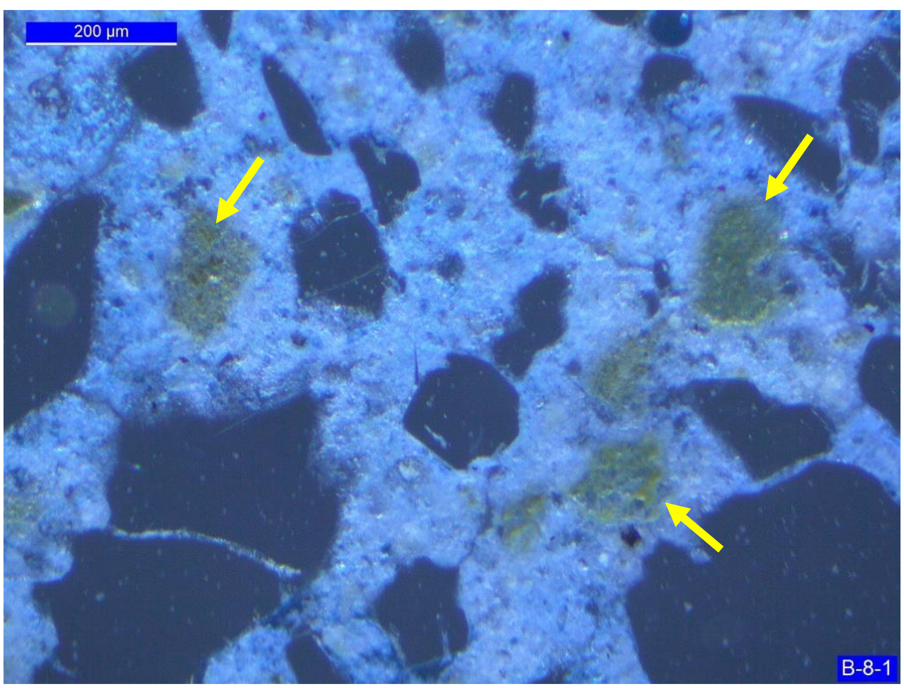

Figure A10. Coarse residual cement particles (arrows) in the concrete body.

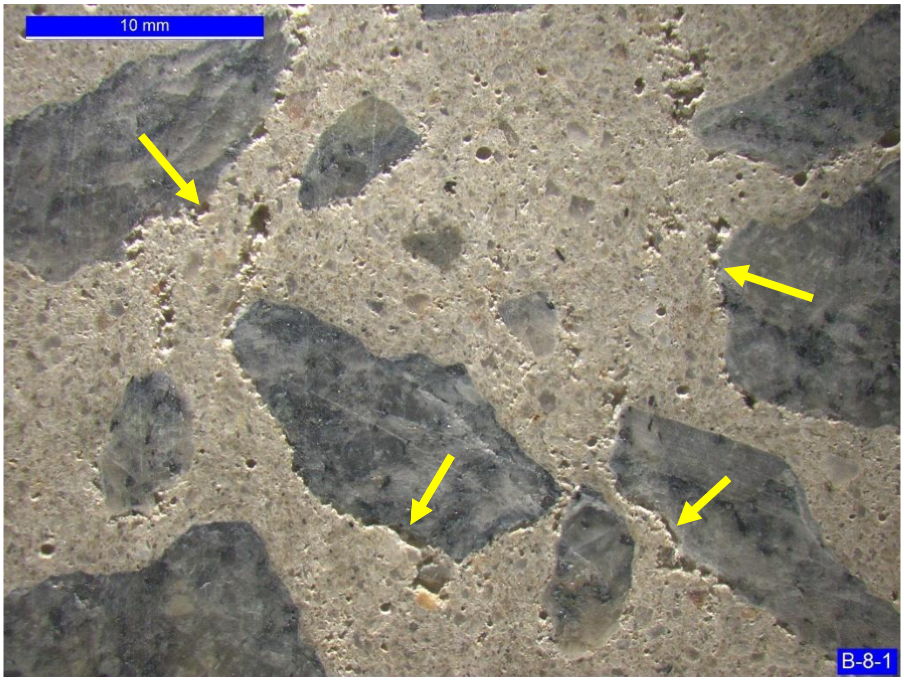

Figure A11. Irregularly shaped voids (arrows) adjacent coarse aggregates, pictured for Core B-8-1.

APPENDIX B. METHODOLOGY

Petrographic Examination

A nominally 1-inch-thick slice was sectioned longitudinally along the middle axis of Cores B-7-1R, B-7-2L, B-8-1, and B-8-2 using a water-cooled continuous-rim diamond saw blade. The resulting planar surfaces of each slice were then lapped using progressively finer abrasives to achieve finely ground, matte surfaces suitable for examination with a stereomicroscope. Laboratory-induced fresh fractured surfaces were prepared to study the carbonation depth, paste-aggregate bond, and other paste characteristics (luster, hardness, etc.). Lapped and fractured surfaces were examined using a stereomicroscope at magnifications up to 90X. A thin section was prepared from a portion of the exterior of each core to assess the paste microstructure, surface distress, and secondary deposits. The thin sections were examined using a petrographic (polarized light) microscope at magnifications of 50X to 630X. The samples were examined using methods outlined in ASTM C856, *Standard Practice for Petrographic Examination of Hardened Concrete*.

Modified Point-Count

Volumes of the concrete constituents, including air, paste, and aggregate, were measured for Core B-7-2L as part of the current studies. Core B-7-2L was selected for the study to be representative of the examined core samples. The studies were conducted in accordance with Procedure B, *Modified Point-Count Method*, of ASTM C457, *Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*.

A total of 1387 points were counted over a total traverse length of 199 inches and an area of 28 square inches at a magnification of 50X.

Storage: Sixty days after completion of our studies, the samples will be discarded unless the client submits a written request for their return. Shipping and handling fees will be assessed for any samples returned to the client. The client may request that WJE retain samples in storage in our warehouse for an annual fee. Any hazardous materials that may have been submitted for study will be returned to the client, and shipping and handling fees will apply.